TRENDS IN THE DESIGN AND PERFORMANCE OF HIGH-SPEED PROPELLERS

By Eugene C. Draley, Blake W. Corson, Jr., and John L. Crigler

Langley Aeronautical Laboratory

INTRODUCTION

Recent propeller research conducted by the National Advisory Committee for Aeronautics has been of sufficient scope to indicate clearly the most promising trends to be followed for the development of efficient propellers for operation at transonic speeds. The papers in the section, Propellers for Aircraft, have presented a few of the more significant results of investigations dealing with blade-section thickness, advance ratio, sweep, dual rotation, vibration, and flutter. The purpose of this paper is to consolidate the conclusions indicated by this work to give direction to the development of high-speed propellers and to consider the physical characteristics and performance of the resulting type of propeller.

SYMBOLS

a	speed of sound in air, feet per second
b	blade chord, feet
D	diameter, feet
h	blade-section maximum thickness, feet
L/D	lift-drag ratio
M	Mach number
n	rotational speed, revolutions per second
R	radius to propeller tip
r	radius to blade section
T	thrust, pounds

[redacted]

[redacted]

β blade angle, degrees

η propeller efficiency

BLADE-SECTION THICKNESS RATIO

The factor shown to have the strongest effect in reducing compressibility losses on propellers is the use of thin blade sections. Figure 1 provides a summary of the information concerning the effects of blade thickness ratio on propeller performance. In the lower part of this figure is shown the variation of the maximum value of section lift-drag ratio with section Mach number for three 16-series airfoil sections having thickness ratios of 8, 5, and 3 percent. In the lower speed range, represented by the solid parts of the lines, the data were obtained from the integration of propeller blade-section pressure distributions measured in the Langley 16-foot high-speed tunnel. For the higher speeds, indicated by the dash lines, the values were calculated by use of two-dimensional supersonic airfoil theory. The results clearly indicate the large improvements in lift-drag ratios at transonic and supersonic speeds associated with reductions in thickness ratio. While the differences in lift-drag ratio at supersonic speeds do not appear to be large, the percentage differences are very large, being of the same order of magnitude as shown at the lower speeds. In the upper part of the figure is plotted some of the experimental results obtained from the Langley 8-foot high-speed tunnel tests (as presented by Richard T. Whitcomb, James B. Delano, and Melvin M. Carmel) showing the variation of maximum efficiency with forward Mach number. For a blade angle of 60° at the 0.75 radius and advance ratio of approximately 3.8, results are presented for three propellers. Two of the propellers differed only in thickness ratio. The thicker propeller was 8 percent thick and the thinner, 3 percent at the design station, $\frac{r}{R} = 0.7$ (NACA 4-(0)(03)-045 and NACA 4-(0)(08)-045 propellers). This figure indicates the improvement in propeller performance corresponding to the increase in lift-drag ratio indicated in the lower part of the figure as obtainable by the use of thinner sections. Not only has a large delay in the onset of compressibility effects been obtained, but the magnitude of the adverse effects are considerably diminished by the use of the thinner blade sections. As a result, the 3-percent-thick propeller is 15 percent more efficient than the 8-percent-thick propeller at a forward Mach number of 0.9. Thus, with blade-section thickness ratios of the order of 3 percent, propeller efficiencies of 70 percent or more can be obtained at forward Mach numbers near 0.9.

For purposes of comparison, there is also included in the upper figure a curve representing the experimental results for the

[redacted]

6-percent-thick swept propeller tested in the Langley 8-foot high-speed tunnel. The efficiency for this propeller, swept 45°, falls only slightly above values which would be expected of an unswept 6-percent-thick propeller. When it is considered that the practical stress and hub problems for a swept propeller are actually more severe than those for a 3-percent-thick straight propeller, it is concluded that the use of sweep in propellers is less effective than the use of very thin blade sections for maintaining good efficiency at transonic speeds and therefore does not warrant consideration in the design of high-speed propellers.

ADVANCE RATIO

The values of blade-section lift-drag ratio presented in the lower part of figure 1 have been used in calculating the performance of a family of propellers in which the diameter has been varied so that each of these propellers would absorb 5200 horsepower at a forward Mach number of 0.90 and at an altitude of 40,000 feet. The results are presented in figure 2. For these calculations, it is assumed that the propeller blade sections operate at maximum values of lift-drag ratio and that an ideal type of blade loading is obtained under all operating conditions. Such calculations, however, have been shown to be reliable by the comparison made in a previous paper by Whitcomb, Delano, and Carmel, between calculated and experimental results. In the lower left-hand corner the assumed variation in the thickness ratio of the blade sections is indicated. Calculations have been made for values of the advance ratio of 2, 4, and 6. Attention is called to the fact that these calculated results differ from both the calculated and the experimental results for the 3-percent-thick propeller presented in the paper by Whitcomb, Delano, and Carmel, in that each of these propellers has been designed to operate at a fixed value of power, and the disk loading is considerably higher than for the cases considered by Whitcomb, Delano, and Carmel. Hence, the level of the low-speed efficiencies is lower because of greater induced losses. In addition, the inboard sections for these propellers are somewhat thinner than those previously discussed and, consequently, the adverse effects of compressibility are less.

At low speeds the calculated values of efficiency range from 83 to 87 percent. Note that the inversion point, the value of Mach number above which best efficiency is obtained with the low-advance-ratio propeller, occurs at a much higher value of Mach number than was obtained with the thicker propeller considered in the paper by Whitcomb, Delano, and Carmel. For these thin propellers, the point of intersection for the three values of advance ratio considered occurs at a forward Mach number of 0.925, and only at higher speeds does there appear to be an efficiency advantage obtainable by the use of low advance ratio. Of interest also is the fact that at speeds above forward Mach numbers of about 0.9 and below 0.6, the efficiency of the low-advance-ratio propeller is equal to or better than the efficiencies for the other advance ratios; however, in the speed range between these two Mach numbers, the propeller having an advance ratio of 4 has as much as 5 percent greater efficiency. If for a design speed of about 0.9 or greater the cruising speed were selected to fall in the intermediate range where best efficiency is obtained at other advance ratios, some sacrifice in cruising performance would result. With the relatively high levels of propeller efficiency indicated, it might be expected that the selection of the cruising speed would be determined by the characteristics of the airplane rather than by those of the propeller, particularly if the airplane drag force-break Mach number should lie in the cruising speed range. In that case, the selection of a cruising speed above the Mach number for drag force break would be impractical because relatively low values of airplane lift-drag ratio would be encountered.

While only small efficiency advantages accrue from the use of a thin low-advance-ratio propeller in the Mach number range around 0.9, consideration of propeller diameter is an important factor which would further tend to favor the use of low advance ratio. As shown in the sketches, for the design conditions assumed, a relatively small propeller (diameter of 12 ft) is required for an advance ratio of 2.0; whereas an unusually large propeller (diameter of 26 ft) would be required for an advance ratio of 6.0. The differences in the propeller diameter required are associated with the fact that at a given forward speed, as the advance-diameter ratio is reduced, the rotational speed is proportionately increased so that higher resultant velocities at the blade sections are produced. With increased section dynamic pressure a greater absolute load can be carried by each section or, conversely, a given required total load can be carried by a propeller of smaller diameter. For a forward Mach number of 0.9 all the blade sections of the low-advance-ratio propeller operate at supersonic speeds. The saving in weight occurring because of the smaller diameter of the low-advance-ratio propeller would probably offset any small gains in efficiency associated with the use of the higher-advance-ratio propellers. The low-advance-ratio propeller therefore is recommended principally by its relatively small size.

DESIGN FEATURES OF SUPERSONIC-TYPE PROPELLER

<u>Advance ratio and thickness ratio</u>.- The material thus far presented indicates two important features of a propeller designed for operation

[redacted]

at supercritical speed, namely thin blades and operation at a low value of advance ratio. A tabulation of these and other physical characteristics regarded as desirable for such a propeller is presented in chart I.

Blade width.- With regard to blade width the design trend for the supersonic-type propeller requiring a specified solidity would be toward the use of a few relatively wide blades rather than many blades of narrow width. Recent investigations made by John E. Baker and Arthur A. Regier, indicate that increasing blade width alleviates the flutter problem. The increased stiffness of a relatively wide blade tends to reduce vibratory stresses. For solid metal blades there is no first-order effect upon centrifugal stress of changes in blade width. Increased centrifugal force resulting from an increase in blade width is accompanied by a proportionate increase in blade cross-sectional area carrying the force. For hollow metal blades the same is true in general, but because the forces and stresses are determined by skin thickness as well as by blade width the designer may have better control over the centrifugal stresses in a relatively wide blade than in one of narrow chord.

Two aerodynamic effects influenced by blade width are tip relief and induced loss. Increasing the relative width of a blade in effect reduces its aspect ratio. Investigations at high subsonic speeds of wings differing only in aspect ratio (reference 1) indicate that the adverse effects of compressibility are less pronounced for wings of low aspect ratio than for those of high aspect ratio. Tests of propellers having the same number of blades but differing in solidity (reference 2) have also indicated the beneficial effect of using wide blades when the blade tip sections operate at supercritical speed. Hence, the results of both wing and propeller investigations indicate that some aerodynamic benefit will be realized from the use of a few relatively wide blades rather than a greater number of narrow blades of equal total solidity. Propeller theory indicates that this trend will result in a slightly greater induced loss, but this effect is of second order when the propeller has at least four blades (reference 3).

Practical considerations involved in choosing the blade width are fabrication, weight, and the blade-spinner juncture. The adaptability of relatively wide blades in combination with extremely thin sections further increases the attractiveness of the high-solidity blade. This trend, however, may involve a weight penalty, because for a fixed value of thickness ratio, diameter, and total propeller solidity, blade weight increases directly with blade width. Compensating the increased blade weight, however, is reduction of hub complexity and weight resulting from the use of fewer blades. A definite disadvantage associated with wide blades is the increased difficulty of providing a

[redacted]

juncture between the blade root and spinner which is both aerodynamically clean and mechanically feasible.

Plan form.- Consideration of only the structural aspects of plan form leads to the use of a large amount of taper. By decreasing the mass of the blade tip region and increasing the blade cross-sectional area near the root the maximum centrifugal stress is greatly reduced. The tapered plan form also results in a blade with root sections having relatively large moments of inertia and the blade is therefore less susceptible to vibration and flutter.

Spinner.- Although spinner size is frequently controlled by the design of the aircraft rather than of the propeller, a relatively large spinner is believed to be desirable for use with the propeller type here proposed. A large spinner minimizes the mutual interference of adjacent blade roots and more easily accomodates the mechanism associated with an aerodynamically clean blade-spinner juncture. By reducing the blade length a large spinner of necessity reduces the blade root stresses, but in so doing aggravates hub and spinner stresses. Moreover, all problems encountered in hub and spinner design, fabrication, balance, icing, and maintenance become more severe with increased size.

Blade loading.- A comprehensive discussion of the aerodynamics of a supersonic-type propeller is beyond the scope of this paper. While a radial distribution of load on the blade which results in minimum induced energy loss is believed to be as desirable for this type of propeller as for the subsonic type, this factor is regarded as of secondary importance in comparison with the effects of section lift-drag ratio and blade stresses. Experience with subsonic propellers has shown that operation over a wide range of advance ratio and blade angle, in which distribution of blade load underwent drastic changes, resulted in negligible effect on propeller efficiency. Associated with blade loading, however, is the estimation of stream angle with reference to the blade sections which is an important factor in obtaining best values of section lift-drag ratio. Adequate theory exists for the design of subsonic and completely supersonic propellers. For the transonic speed range, theory is incomplete.

Blade section.- When blade sections are made extremely thin the basic shape of the sections becomes of secondary importance. Recent work has indicated that thin subsonic sections with rounded leading edges perform as well at transonic and low-supersonic speeds as do double-wedge and biconvex sections and are naturally superior at subcritical speeds. Because the operation of a high-solidity propeller is similar to that of a cascade in that considerable curvature of the flow takes place in the propeller disk, more camber may be required for a propeller section than for an airfoil section exerting the same lift. The mutual effects of blade-section camber and propeller solidity requires investigation at transonic speeds.

BLADE-FORM CURVES

Figure 3 presents an illustrative sketch and blade-form characteristics of the proposed supersonic-type propeller. The design value of advance ratio, thickness ratio, solidity, and taper conform to the recommendations listed in chart I. The values shown are those assumed in calculating the performance of the 12-foot-diameter single-rotation propeller discussed in figure 2. The rectangular appearance of the blades in the front view is merely the projected view; the blades are actually tapered. Note that in this propeller the portion of the blade extending out of the spinner is only 4 feet long. The calculated maximum centrifugal stress for the propeller is approximately 16,500 pounds per square inch at 2200 rpm for solid duralumin blades.

DUAL ROTATION

Consideration of single-rotation-propeller theory has indicated that best efficiency at flight Mach numbers near 0.9 and above can be obtained by operation at an advance ratio of approximately 2.0.

Two factors which influence the operation of the dual-rotation propeller make it inherently well adapted to operation at high values of advance ratio. These factors are recovery of most of the induced rotational loss and the shift toward the inboard radii of the blade load. At high values of advance ratio, most of the induced loss for a single-rotation propeller appears as rotation of the slipstream; in a dual propeller a large part of the slipstream rotational energy is recovered; hence at subcritical speeds the dual propeller can operate efficiently at high values of advance ratio at which the single propeller would be hopelessly inefficient. At a given forward speed, high advance ratio is synonymous with low rotational speed and low section speed; hence the dual-rotation propeller can maintain subcritical section operation at high forward speeds by operation at high advance ratio. An attempt to follow this process with a single-rotation propeller results in large rotational loss and unacceptably low efficiency.

In comparison with a single-rotation propeller the blades of a dual-rotation propeller inherently carry a greater portion of their load on the inboard stations and less outboard near the blade tips (reference 4). This fact is equivalent to saying that the blade-tip region of the dual-rotation propeller operates at lower values of lift coefficient or has relatively less solidity than a comparable single-rotation propeller. Consequently, the adverse effects of compressibility, which in subcritical operation become manifest first near the blade tip sections, are less severe for the dual-rotation than for the single-rotation propeller and, therefore, permit the dual-rotation propeller to maintain subcritical operation at higher forward speed than can the single-rotation propeller.

Experimental results showing the variation of efficiency with flight Mach number at values of Mach number up to 0.925, for a two-blade single-rotation propeller and an eight-blade dual-rotation propeller (given in papers by Richard T. Whitcomb, James B. Delano, and Melvin M. Carmel and Robert J. Platt, Jr., and Jean Gilman), are presented in figure 4. Although the data for each propeller were taken at an approximately constant value of advance ratio, 3.8 for the single rotation and 7.0 for the dual rotation, the values in each case are close to those for envelope efficiency in the critical range. While the disk power loading for the dual-rotation propeller was much higher than that of the single-rotation propeller, the efficiency of the dual-rotation propeller was equal to that of the single-rotation propeller up to a forward Mach number of 0.85, indicating that the dual-rotation propeller was operating effectively in recovering the slipstream rotational energy. The design values of thickness ratio for these propellers were 0.03 for the single and 0.05 for the dual. It is safe to assume that the comparison would have been more favorable for the dual-rotation propeller, if the design thickness ratio had been the same for both. From this comparison based on efficiency alone it is concluded that dual-rotation propellers should be given due consideration for application at flight Mach numbers up to 0.85.

An important point brought out in this comparison (fig. 4) is that at forward Mach numbers above 0.85 the single-rotation propeller operating at a relatively low value of advance ratio and with high rotational speed is superior to the dual-rotation propeller operating at high advance ratio. At a forward Mach number of 0.9, the most effective sections of the single-rotation propeller have passed through their critical speed range into supersonic operation and the propeller efficiency has begun to level off at a relatively high value, about 0.73. At the same value of flight Mach number, the sections of the dual-rotation propeller, because of the high value of advance ratio, are still operating in the midrange of critical speed, and further increase in Mach number can result only in a continued decrease in efficiency.

At this point the question arises as to the desirability of designing a dual-rotation propeller for operation at a relatively low value of advance ratio. This design change is aerodynamically feasible.

[redacted]

Presumably the efficiency of the dual-rotation propeller at supercritical speeds could be made to level off at as high a value as attained by the single propeller, but in so doing the advantages of the high-advance-ratio dual-rotation propeller would be sacrificed. Further, because operation at low advance ratio is accompanied by an increase in rotational speed, the mechanical design problems for the dual-rotation propeller would be much more severe than for the single-rotation propeller.

THRUST CHARACTERISTICS

In order to provide a more realistic indication of the performance of both a typical low-advance-ratio single-rotation propeller and a high-advance-ratio dual-rotation propeller of the types already indicated to give good performance, figure 5 has been prepared in which calculations of the thrust and efficiency characteristics for a wide forward speed range are presented. The calculations have been made to represent the thrust produced by the two propellers of different type when absorbing 7500 horsepower at sea level, and for powers varying from 4150 horsepower at 400 miles per hour to 5200 horsepower at 600 miles per hour at an altitude of 40,000 feet. These powers have been selected as typical shaft powers obtained for gas-turbine power plants. It has been assumed that the design point of the two propellers was 5200 horsepower at the 600 miles per hour at 40,000 feet altitude, which corresponds to a forward Mach number of 0.9. The calculations of efficiency and thrust have been determined by estimating the variations in advance ratio and other propeller-operating conditions occurring when changes in forward speed and power were made. Thus, the thrust curves represent typical thrust-available characteristics for a turbopropeller combination.

It should be emphasized that the thrust levels in the high-speed altitude conditions are of the order of 2500 pounds of thrust in both cases. Such thrust values are thus representative of very large jet engines. Of particular interst is the fact that these values can be obtained with a 12-foot-diameter propeller. Note that both the efficiency and the thrust of a dual-rotation propeller are somewhat greater than for the single-rotation propeller in the speed range of from 400 to 550 miles per hour, owing to the smaller induced losses of the larger diameter dual propeller. At the maximum-speed case, however, there is a reversal of this trend because of the somewhat greater thickness ratios used in the dual calculations and because of the advantage of low advance ratio in this speed range. These calculations are based on the same type of approach that was used in the papers by Whitcomb, Delano, and Carmel and Platt and Gilman. It was assumed that best lift-drag ratios were obtained all along the blade and that the ideal type of loading was obtained.

[redacted]

For the sea-level case, the relative thrust characteristics of the two propellers are diametrically opposed to what would at first be expected. The dual-rotation propeller produces considerably less thrust than the single-rotation propeller, in spite of its larger diameter. This relatively lower thrust in the lower-speed range, below approximately 250 miles per hour, occurs because the blades of the dual-rotation propeller absorbing high power at low rotational speed become stalled. For high advance-diameter ratios, the resultant velocities all along the blade radius for a propeller are largely made up from the forward-speed component, and thus when the forward speed is greatly reduced the resultant velocities become so low that the blade sections exceed their maximum lift in absorbing the specified power. An indication of the relative section speeds for the two propellers is shown by the values of the rotational tip Mach number given in the upper right-hand part of the figure. The single-rotation propeller has a rotational tip Mach number of 1.195 as compared to 0.412 for the dual-rotation propeller. The corresponding values of rotational speed are 2200 rpm and 650 rpm, respectively. If the design speed for the dual-rotation propeller were somewhat reduced, the blade stalling problem would be correspondingly reduced and it appears that in certain specific applications the problem of blade stall might be avoided. This result illustrates that a design compromise problem can be expected in the case of the dual-rotation propeller. It also illustrates the usefulness of a two-speed gear to permit increases in the rotational speed at the low forward speeds. In such a case, both the thrust and the efficiency characteristics of the dual-rotation propeller would be greatly improved and would exceed the values shown for the single-rotation propeller by a considerable margin.

RANGE

The propulsive efficiency levels shown for propellers are considerably in excess of the corresponding efficiency values for jet engines, even at the maximum speeds shown in figure 5. On the other hand, it is known that the turbopropeller-engine combinations would be considerably heavier than turbojet engines, and thus it becomes of interest to establish the relative performance of an aircraft when the advantages in efficiency and disadvantages in weight of turbopropeller engines as compared to turbojet engines are considered. Figure 6 has been prepared to illustrate these effects. In this figure, the range characteristics of a given airplane have been calculated for two cases. The airplane assumed had a gross weight of 200,000 pounds, a wing loading of 70 pounds per square foot, and the power-plant weight plus the fuel weight was taken as 52 percent of the gross weight. The calculations were based on cruise at constant speed at 40,000 feet altitude.

The first case involves the use of a turbopropeller installation in which typical fuel-consumption figures for gas-turbine engines have been used (approx. 0.45 lb/shaft hp-hr). The propeller performance figures used are the same as those previously presented for the 12-foot-diameter single-rotation propeller having an advance-diameter ratio of 2. It should be noted that the calculations are presented to include a range of power-plant weights, because an analysis of typical airplanes using such power plants has indicated that a relatively wide range of weights might occur in specific cases. Moreover, the use of a dual-rotation propeller instead of a low-advance-diameter-ratio single-rotation propeller would increase the power-plant weight. The band shown is considered to represent the typical ranges through which the power-plant weights might vary.

The second case has been calculated for the same airplane and the same conditions of flight for the airplane, but with the use of turbojet engines. These characteristics have been based upon the use of typical efficiency and specific fuel-consumption figures (approx. 1.3 lb/thp-hr) for jet engines and, as a matter of fact, when compared on the same basis the specific fuel consumptions for the two engines are almost the same. The resulting comparison, therefore, between the airplane with the turbopropeller combination and the airplane with the turbojet engine results primarily from the differences in propulsive efficiency and the weight differences between the installations. The drag and lift-drag ratios for the two cases were almost the same, the lower drag and higher lift-drag ratios were used with the jet-engine installation. It should be noted that these calculations are made for a specific airplane, and while the comparisons shown are considered to be typical, there would be expected in some individual cases rather marked deviations from the absolute values and shapes of individual curves shown, depending upon the specific parameters involved in any case.

The example taken clearly indicates that despite the greater weights assumed for the turbopropeller engines, greater range characteristics were obtained with that type of engine than for the turbojet engines even for the highest speeds at which these calculations were made. It is interesting to note that at a Mach number of 0.9 the gain in efficiency associated with going from turbojets to propellers is sufficiently great so that the turbopropeller system would still show a gain in range in the case where the power plants were more than twice as heavy for the turbopropeller as for the turbojet. (Compare the power-plant gross-weight ratio of 0.12 for the turbojet with the curve for power-plant weight to gross-weight ratio of 0.25 for the turbopropeller.) Thus, it appears that through the use of the types of propellers herein discussed, having very thin sections and utilizing in general small-diameter, low-advance-diameter-ratio propellers that the gain in propulsive efficiencies associated with these propellers as compared to jet-engine efficiencies can be sufficiently great to offer increases in the range of an airplane of specified gross weight and wing loading despite the greater weights inherent in the turbo-propeller engines.

CONCLUDING REMARKS

In summary, it appears that through the use of a low-advance-diameter-ratio supersonic type of propeller having relatively small diameter and having very thin sections, propeller efficiencies of the order of 75 percent or greater are possible at high subsonic Mach numbers. Dual-rotation propellers operating at high advance-diameter ratios also appear to give efficiencies comparable to the single-rotation propeller of the type just mentioned up to speeds just below Mach numbers of 0.9. The difference in the propulsive efficiency of these types of propellers as compared to typical efficiencies for jet engines are indicated to lead to an improvement in the range characteristics of a long-range airplane despite the greater weights associated with the turbopropeller combinations. Thus, the use of a propeller should be given consideration in the design of long-range aircraft for forward Mach numbers up to 0.9.

REFERENCES

1. Stack, John, and Lindsey, W. F.: Characteristics of Low-Aspect-Ratio Wings at Supercritical Mach Numbers. NACA Rep. 922, 1949.

2. Delano, James B.: The Effect of High Solidity on Propeller Characteristics at High Forward Speeds from Wind-Tunnel Tests of the NACA 4-(3)(06.3)-06 and NACA 4-(3)(06.4)-09 Two-Blade Propellers. NACA RM L6L19, 1946.

3. Crigler, John L., and Talkin, Herbert W.: Charts for Determining Propeller Efficiency. ACR L4I29, 1944.

4. Crigler, John L.: Application of Theodorsen's Theory to Propeller Design. NACA RM L8F30, 1948.

CHART-I
DESIRABLE CHARACTERISTICS – SUPERSONIC – TYPE PROPELLER

A. DESIGN $\frac{V}{nD} \approx 2.0$

B. THINNEST PRACTICAL BLADE SECTION

C. WIDE BLADE	– REDUCES VIBRATION AND FLUTTER PROBLEM
	– CENTRIFUGAL STRESS PROBLEM NOT AGGRAVATED
	– GREATER EFFECT OF TIP RELIEF
	– NEGLIGIBLE INCREASE IN INDUCED LOSS
	– POSSIBLE ADVANTAGES IN FABRICATION
	– POSSIBLE WEIGHT PENALTY
	– GREATER BLADE-SPINNER JUNCTURE PROBLEM
D. TAPERED-BLADE PLAN FORM	– REDUCES CENTRIFUGAL STRESS PROBLEM
	– REDUCES VIBRATION AND FLUTTER PROBLEM
E. LARGE SPINNER DIAMETER	– REDUCES BLADE-ROOT INTERFERENCE
	– REDUCES BLADE STRESS PROBLEMS
	– REDUCED BLADE-SPINNER JUNCTURE PROBLEM
	– HUB AND SPINNER PROBLEMS INCREASED

[redacted]

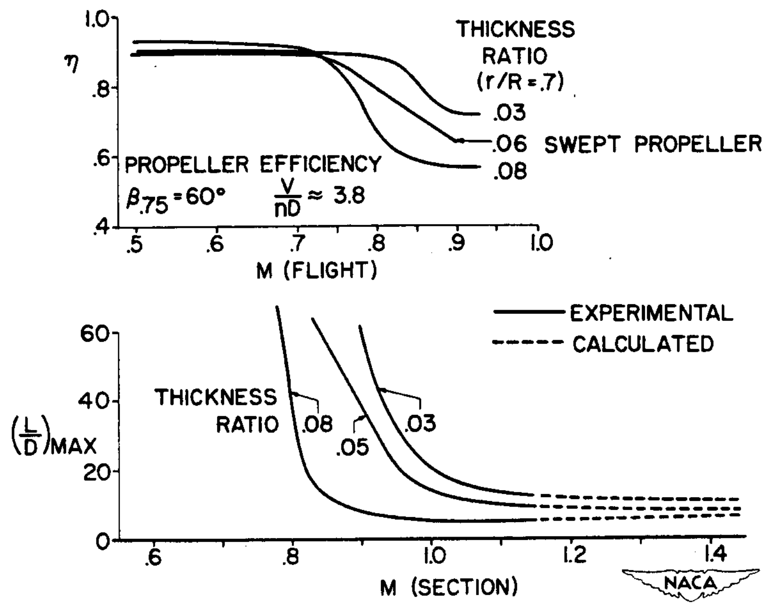

Figure 1.– Effect of Mach number and thickness ratio on blade-section characteristics and propeller efficiency.

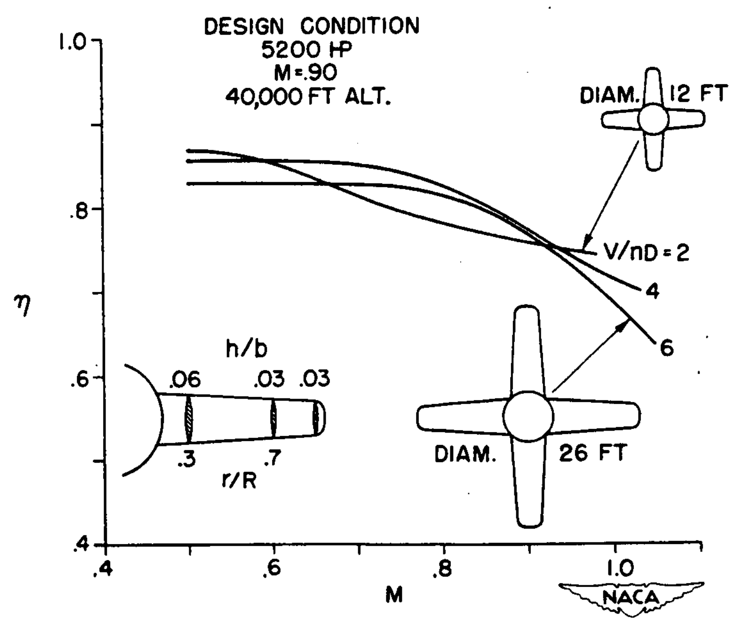

Figure 2.– Calculated effect of Mach number and adverse ratio on propeller size and efficiency.

[redacted]

DE[redacted]IFIED

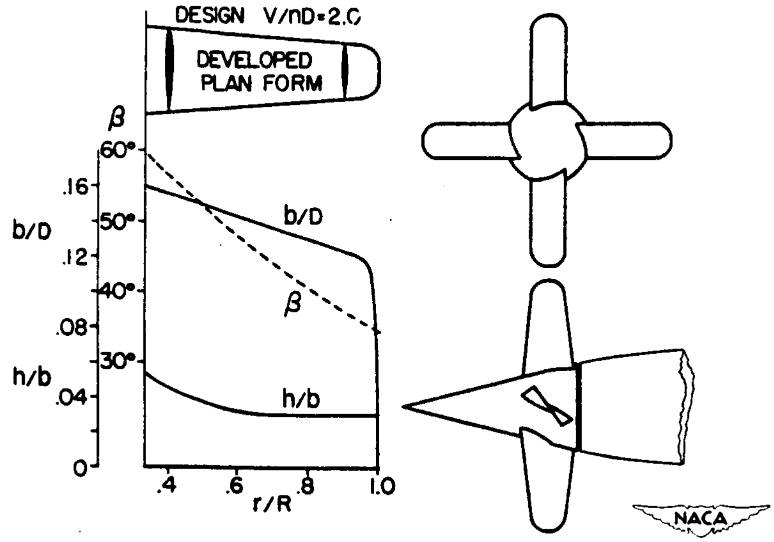

Figure 3.- Physical characteristics of supersonic-type propeller.

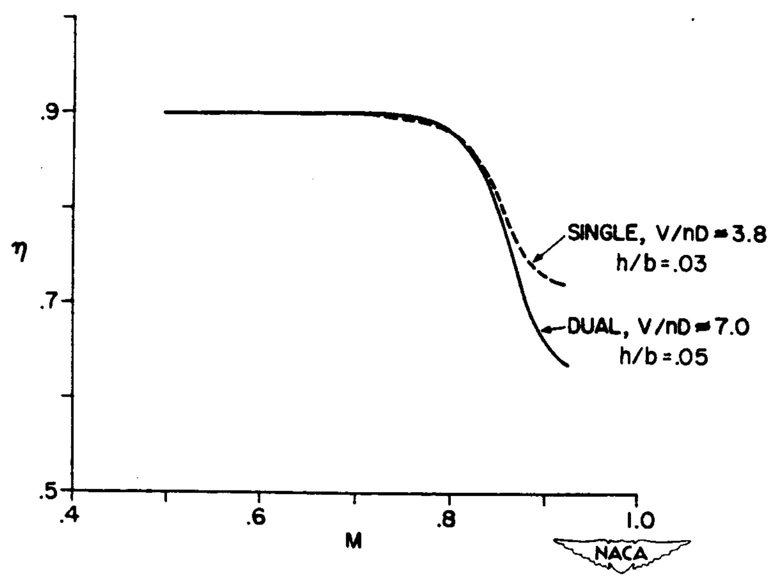

Figure 4.- Comparison of experimental efficiencies for a single-rotation and a dual-rotation propeller.

[redacted]

[redacted]

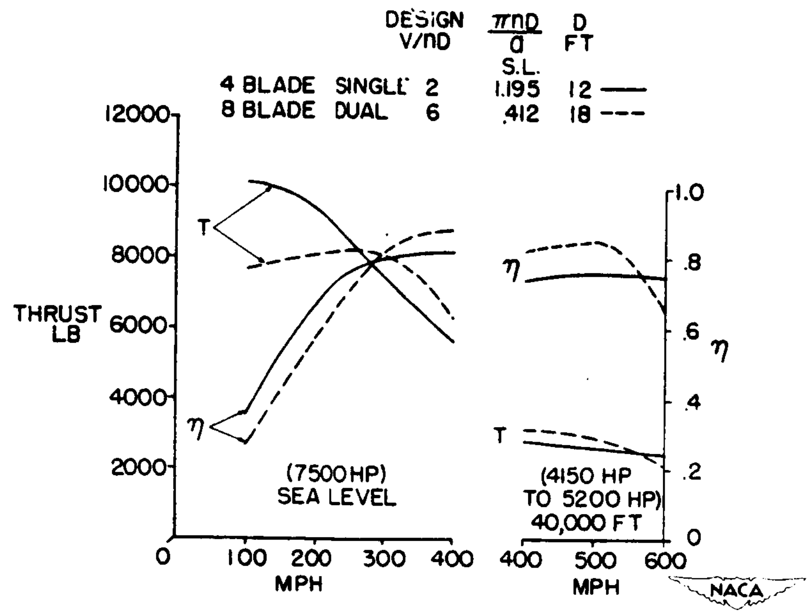

Figure 5.- Calculated thrust and efficiency characteristics for a single-rotation and a dual-rotation propeller.

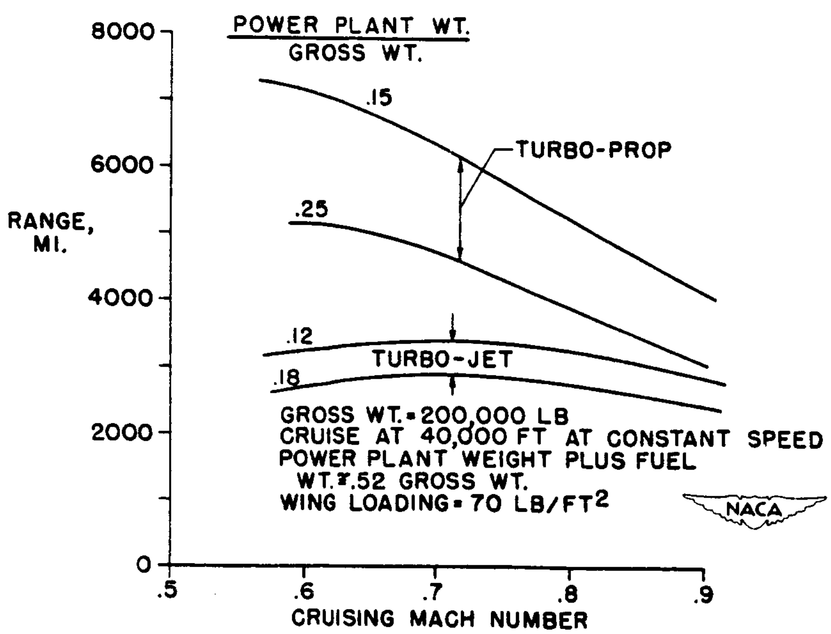

Figure 6.- Calculated range characteristics of an airplane powered by a turbojet or turbopropeller.

[redacted]